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Probabilistic Coverage Preserving Protocol with Energy Efficiency in Wireless Sensor Networks

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Abstract- **In this paper, we propose a *k*-coverage preserving protocol to achieve energy efficiency while ensuring the required coverage. In our protocol, we try to select a minimal active set of sensor nodes to reach energy conservation and maintain a complete area *k*-coverage. We model this problem as a minimum set cover problem and solve it by using a heuristic greedy algorithm. Based on the *k*-coverage preserving protocol, we then propose a protocol to deal with the probabilistic *k*-coverage requirement, in which each sensor could be assumed to be able to detect a nearby event with a certain probability. In the probabilistic *k*-coverage protocol, any point in the monitoring region can be sensed by at least *k* sensor nodes no lower than a confidence probability. Finally, we evaluate the performance of our protocols with simulations.**

I. INTRODUCTION

One of the main issues in the wireless sensor networks (WSNs) is coverage problem [5, 14]. In general, this reflects how well the designed region is monitored by sensors. It is said that a point p is covered by a sensor node s if their Euclidian distance denoted by $|ps|$ is less than the sensing range of s, R_s, i.e., $|ps| < R_s$. The multiple coverage requirements are regularly called the k-coverage problem, that is, every point in the whole target area is covered by at least k distinct sensors, where k is a predefined constant. Some applications may require $k > 1$ when a stronger environmental monitoring is necessary, such as target tracking and triangulation-based positioning protocols, or for fault-tolerant purpose. On the other hand, as the result of the limited capabilities and constrained resources of sensors, they are usually deployed in high densities. Dense deployment not only helps improve a sensor network's reliability, it also extends its longevity. Since nodes are deployed with high redundancy, not every node in the sensor network needs to be active for sensing and communicating all the time. A fundamental problem is how to minimize the number of active nodes for energy conserving while still achieving acceptable quality of service for coverage.

Energy consumption has been an important factor in WSNs design because sensors are typically battery-powered and, once deployed; each sensor is expected to work for months or years without any battery replacement. In this paper, we propose a *k-coverage preserving protocol* to achieve energy-efficiency while ensuring the required coverage. In this protocol, we model the area coverage problem as a minimum set cover problem which was proven to be NP-complete [3], and a centralized polynomial-time approximation is indicated, that is, a greedy approach algorithm. The goal of our approach is to provide the required sensing coverage over a geographic region by determining a minimum number of active nodes while scheduling the others to sleep, as this directly impacts the conservation of sensor energy resources as well as extending the lifetime of the total network.

Furthermore, since sensing is the significant assignment for the proper function of WSNs, the sensing coverage region of a sensor node is always assumed uniform in all directions (unit-disc model). Most of the recent research works suppose this to be the ideal simplified circular sensing model following the binary detection model. An event that occurs within the sensing radius of a node is always assumed to be detected with probability 1 while any event outside this circle of influence is assumed to be 0. Unfortunately, this is not appropriate for the realistic sensing model, as the sensing capabilities of networked sensors are affected by environmental factors. Each sensor could be assumed to be able to detect a nearby event with a certain probability, which is affected by the distance between the sensor location and the location of the event. In general, a relaxed probabilistic coverage, where any point in a sensing region is sensed with a certain probability at any time, is a more appropriate approach to have practical considerations at the design stage [15]. Therefore, we propose a protocol based on the k-coverage preserving protocol to deal with this *probabilistic k-coverage problem*.

The remainder of this paper is organized as follows. In Section II, we review the related work. In Section III, we present the energy-efficient k-coverage preserving protocol and the probabilistic k-coverage protocol. Section IV evaluates the performance of our protocols in simulations. Finally, we conclude this paper in Section V.

II. RELATED WORK

In previous literatures, coverage problems can be classified into the following types [2]: *point coverage*, *barrier coverage*, and *area coverage*. *Point coverage* covers a set of specific points (targets). The authors in [1] present a scheme to extend a sensor network's operational time by organizing the sensors into a maximal number of disjointed set covers that are activated successively. The k-connected coverage set problems addressed in [12] has the objective of minimizing the total energy consumption while obtaining k coverage for reliability. A recent issue in [6] defined the concept of a *k-barrier coverage,* which derives a theoretical foundation to determine the minimum number of sensors to be deployed so intruders crossing a barrier of sensors will always be detected by at least k active sensors.

Area coverage is the most discussed coverage problem, where the main objective of the sensor network is to cover (monitor) an area. In the category of area coverage, sensors are used in greater numbers for field operation, and efficient sensors deployment becomes obvious strategies to maintain coverage. Hence, some specific deployment algorithms existing in the literatures try to find out the optimal sensor placement locations in order to maintain sufficient coverage [4, 15]. The drawback of these algorithms is that they are only applicable for manual predetermined deployment, but they must be

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inaccessible in some dangerous environments such as battlefields, chemically polluted occasions, disaster areas and air drops. Thus, in these scenarios, random deployment is the only feasible method. This means that the on-duty period or the minimal covering active set cannot be pre-determined. The sensor nodes must be able to compute this online, by executing the appropriate algorithms. Conserving energy by selecting the minimal set of active nodes to increase the network lifetime has been an active area of research. If some nodes share the common sensing region and task, we can turn off some of them to conserve energy and thus extend the lifetime of the network. This issue has been extensively studied recently [9, 13, 10]. We can classify these literatures for single and multiple coverage problems according to the requirement of the coverage degree.

For single coverage requirements, the authors in [13] propose a distributed, probing-based density control algorithm to put some nodes in a sensor-dense area into a doze mode to ensure a long-lived, robust sensing coverage. The probing range can be adjusted to achieve different levels of coverage overlap, but it cannot guarantee complete coverage. In [9], the authors develop a sponsored area algorithm which aims to provide complete coverage using its off-duty eligibility rules. Whenever a sensor node receives a packet from one of its working neighbors, it calculates its sponsored area. If the union of all the sponsored areas of a sensor node covers the coverage disk of the node, the node turns itself off. The defect of this sponsored area approach is that it may be less efficient than a hexagon based GAF-like [11] algorithm.

For the k-coverage problem, two distributed coverage service protocols are proposed in [8], which identify redundant sensor nodes of the desired degree of coverage to turn off their sensing units. They identify the redundant nodes by coverage-service algorithm and activate the sensing units of only the required sensor nodes in order to achieve lower computational and message overhead. A Coverage Configuration Protocol (CCP) that can provide different degrees of coverage, and at the same time, maintain communication connectivity is presented in [10]. The authors claim that coverage can imply connectivity as long as the sensors' communication ranges are not less than twice their sensing range.

Most of the aforementioned coverage-related protocols assume uniform sensing ranges and binary detection models. The sensing signal-strength is easily affected by environmental factors such as interference, multi-path, fading, and so on. We can assume that the probability of detection of a target by a sensor varies exponentially along with the distance between the target and the sensor. However, the probabilistic coverage problem for sensor networks has been explored in some research efforts. The proposed algorithms in [7, 4] address coverage optimization under the constraints of imprecise detections and of terrain properties. The drawback of these analyses is that they all rely on some kind of specific placement method like grid-based or square-based methods that the analytical model of probabilistic coverage cannot adapt randomly to the deployment situation. In this paper, we propose a probabilistic k-coverage protocol with energy efficiency in wireless sensor networks.

III. Our Protocols

In this section, we first propose an energy-efficient k-coverage preserving protocol. We then propose a protocol to solve the probabilistic k-coverage problem. Here, we address the essential assumptions used in our protocol design as follows. The entire sensor nodes are deployed randomly and uniformly in regular (rectangle) monitoring regions. Each sensor node knows its own location, e.g., through GPS technique or other localization protocols. Every node is expected to have a uniform node lifetime, and the power declines also uniformly with time. The sensing area of every node is assumed to be circular. Every node has the same sensing range (R_s) and communication range (R_c). The communication range is greater than two times that of the same sensing range. This is a sufficient condition for coverage to imply connectivity, i.e., for a set of sensors that sufficiently cover a monitoring region, the communication graph is connected if $R_c \geq 2R_s$. Consider a sensor network with large amount of sensor nodes that are deployed randomly over a 2-dimension convex monitoring region $\boldsymbol{R}$. We are given a set of sensors, $S = \{s_1, s_2, \ldots, s_n\}$ and assume that each sensor s_i is located at coordinate (x_i, y_i) and has R_s and R_c, for $1 \leq i \leq n$. Each sensor node s_i is also aware of its current residual energy, denoted as E_i, for $1 \leq i \leq n$.

Definition 1: An arbitrary point a in $\boldsymbol{R}$ is said to be covered if it is within s_i's sensing range, i.e., $|\, as_i \,| < R_s$. The monitoring region $\boldsymbol{R}$ is said to be covered if all of the arbitrary points in $\boldsymbol{R}$ are covered by at least one sensor.

Definition 2: The intersection point is a point between any two sensors' sensing circles or any sensor's sensing circle and the boundary of $\boldsymbol{R}$. Let $P = \{p_1, p_2, \ldots, p_m\}$ denote a set of m intersection points. We also denote that $C(i)$ represents the set of intersection points covered by sensor s_i i.e., $C(i) = \{\, p_j \mid p_j$ is the intersection point and $|\, s_i\, p_j \,| < R_s \,\}$.

The authors in [10] prove that, given a coverage degree k, if and only if all intersection points are completely k-covered, the monitoring region $\boldsymbol{R}$ is completely k-covered. So we can transform the area coverage problem of determining the coverage degree to the easier point coverage problem of determining the coverage degrees of all intersection points in the monitoring region $\boldsymbol{R}$. Note that the sensing boundary of each circle is not covered by the sensor. For example, the sensing region $\boldsymbol{R}$ in Fig. 3.1 is completely 1-covered because every intersection point is covered by at least one active sensor.

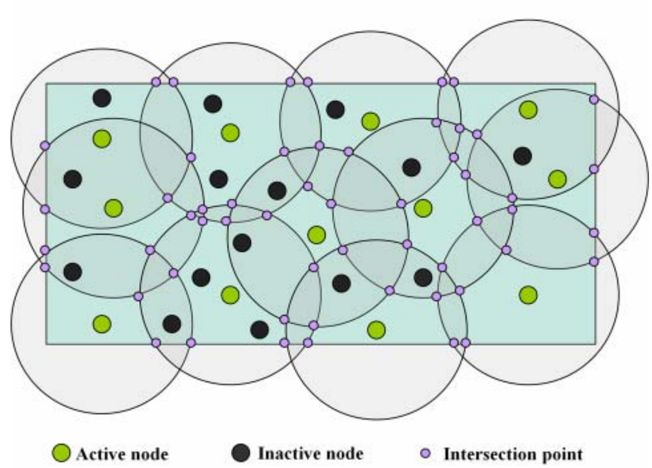


Figure 3.1: Example of the sensing coverage scenario

A. *k-Coverage Preserving Protocol* (*CPP*)

In this subsection, we propose a centralized algorithm such that the monitoring region is sufficiently *k*-covered while still able to conserve a great quantity of energy. The goal of this protocol is to select the minimum active set of sensor nodes to reach the most conserved energy while still guaranteeing adequate coverage of the monitoring region. Since all of nodes in the sensor network are not necessary set to be active all the time, we assume each node is able to switch either to active mode or sleeping mode. In sleeping mode, the node turns off both its sensing and communication components to conserve energy exploitation. We assume that a central data collector node, which we refer to as the Base Station (BS), can coordinate with all sensor nodes. The problem of the sensor node schedule can be accomplished as follows: All of the sensor nodes send their location information to the BS. The BS executes the node eligibility algorithm and then broadcasts the active/sleeping schedule to each node. After receiving the active/sleeping schedule, each node determines itself to be active or sleeping in the sensing period.

It should be noted that the area coverage problem can be reduced to the (intersection) point coverage problem in [10], and we are just concerned about whether each intersection point is covered or not. The BS is known as S (a set of n sensors), P (a set of m intersection points), and $C(i)$ (a set of intersection points that are covered by sensor s_i) by computations after it receives the location of each sensor node. Thus, we can reduce this problem to a classic *Minimum Set Cover* (MSC) problem, which is one of the most studied NP-hard problems [3]. One of the best polynomial time algorithms for approximating MSC is through a greedy algorithm. That is each step chooses the unused set which covers the largest number of remaining elements.

The algorithm for solving the 1-coverage problem is described in Algorithm 3.1. At each round of looping, it will select an unused sensor $s_i \in US$, which covers the largest number of uncovered intersection points (*UIP*). The eligibility rule follows four conditions with the priority being Ⅰ>Ⅱ>Ⅲ>Ⅳ. That is to say, it will select a sensor with the most contribution of *UIP* such that $|C(i) \cap UIP|$ is maximal. If there exists more than one sensor having the same max $|C(i) \cap UIP|$ value, the algorithm will check the second condition and select the one which has the less number of intersection points already covered, i.e., condition $|C(i) \cap (P - UIP)|$ is minimal. If there exist more than one sensor that satisfies condition Ⅰ∩Ⅱ, then the algorithm will choose one which has more residual energy E_i. Unfortunately, if there still exists more than one sensor that satisfies condition Ⅰ∩Ⅱ∩Ⅲ, the algorithm will choose one which has the smallest unique node ID. When we select an unused sensor s_i successfully, we join s_i into minimum set cover and disjoin s_i from the set of all unused sensors and subtract the intersection points that s_i has already covered from *UIP*. By performing the above steps repeatedly, we eventually get a finite set of the minimum set cover.

Algorithm 3.1: *Energy-Efficient 1-Coverage Algorithm*

Input : A finite set of n sensors, $S = \{s_1, s_2, \ldots, s_n\}$ and $E_i > 0$;
A finite set of m intersection points, $P = \{p_1, p_2, \ldots, p_m\}$;
$C(i) = \{ p_j \mid p_j$ is intersection point and $| s_i p_j | < R_s \}$;

Output:
A finite set of the minimum set cover, *MSC*;
$MSC \leftarrow \Phi$; /* *MSC* initially is set to be empty */
$US \leftarrow S$; /* *US* is a temporary set of all unused sensors */
$UIP \leftarrow P$; /* *UIP* is a temporary set of uncovered intersection points */
while $|UIP|$!= 0 **do**
  Given condition Ⅰ: $|C(i) \cap UIP|$ is maximal;
  Given condition Ⅱ: $|C(i) \cap (P - UIP)|$ is minimal;
  Given condition Ⅲ: residual energy E_i is maximal;
  Given condition Ⅳ: node ID i is minimal;
  if (more than one sensor $s_i \in US$ that satisfy Ⅰ);
    if (more than one sensor $s_i \in US$ that satisfy Ⅱ);
      if (more than one sensor $s_i \in US$ that satisfy Ⅲ);
        Select $s_i \in US$ that satisfy Ⅰ∩Ⅱ∩Ⅲ∩Ⅳ;
      else Select $s_i \in US$ that satisfy Ⅰ∩Ⅱ∩Ⅲ;
    else Select $s_i \in US$ that satisfy Ⅰ∩Ⅱ;
  else Select a sensor $s_i \in US$ that satisfy Ⅰ;
  $MSC \leftarrow MSC + s_i$; $US \leftarrow US - s_i$; $UIP \leftarrow UIP - C(i)$;
end while loop;
return *MSC*

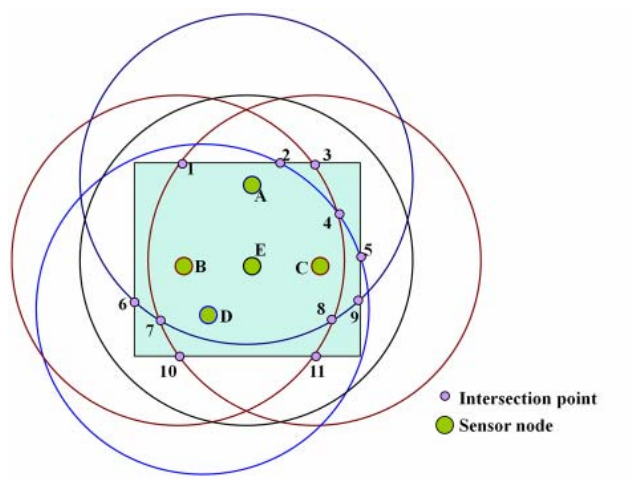


Figure 3.2: An example of 5 sensors and 11 intersections points

Based on the 1-coverage preserving protocol, we can deal with the *k*-coverage problem. Here, algorithm 3.1 should be modified as follows. First, each intersection point p_j has an uncovered degree (UD_j) and initially is set to k. Second, if a sensor is chosen, the uncovered degree (*UD*) of its covered intersection points (i.e., $\forall p_j \in C(i)$) is decreased by one. Finally, if any UD_j is equal to zero, it means that p_j is covered by k sensor nodes sufficiently, and is removed from the set *UIP*. When the finite set *UIP* is empty, it means that all intersection points are covered by at least k sensor nodes.

An example is shown in Fig. 3.2, where $C(A) = \{ p_1, p_2, p_3, p_4, p_5\}$, $C(B) = \{ p_1, p_2, p_6, p_7, p_{10}\}$, $C(C) = \{ p_2, p_3, p_4, p_5, p_8, p_9, p_{11}\}$, $C(D) = \{ p_1, p_6, p_7, p_8, p_9, p_{10}, p_{11}\}$, and $C(E) = \{ p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{11}\}$. Suppose the residual energies E_A, E_B, E_C, E_D and E_E are 100, 90, 80, 70, and 60 units, respectively. We assumed that the required degree of coverage is $k = 2$. So the uncovered degree (*UD*) of each intersection point is set to 2 initially. Following algorithm 3.1, sensor E will be first selected because it satisfies condition Ⅰ, and the *UD* of each intersection point covered by sensor *E* is decreased by one. Sensor *C* will be selected in the next round because it satisfies $\text{I} \cap \text{II}$, and its residual energy is greater than sensor *D*. In this round, the intersection points P_2, P_3, P_4, P_5, P_8, P_9, and P_{11}, will be removed from *UIP*. Finally, the algorithm in this example can guarantee that each intersection point is covered by at least 2 sensors when $MSC = \{E, C, B\}$. In the same way, if the required degree of coverage is $k = 3$, we can obtain $MSC = \{E, C, D, A, B\}$.

B. Probabilistic k-Coverage Protocol

In the aforementioned section, we suppose the assumption of the ideal simplified circular sensing model following the yes/no (1/0) binary detection model. Equation (3.1) shows a binary sensor model that expresses the coverage $C(s_i)$ of any point *p* by sensor s_i:

$$C(s_i) = \begin{cases} 1, & \text{if } |s_i p| < R_s \\ 0, & \text{otherwise} \end{cases} \qquad (3.1)$$

The binary sensor model assumes that the sensor's sensing capability is perfect and has no associated uncertainty. But in reality, when a sensor detects an event based on its measurement, that event can be decoded correctly if the measurement value is above the preset received threshold. Due to signal attenuation and noise, sensing capabilities are affected by environmental factors and will be imprecise. Hence, the coverage $C(s_i)$ needs to be modified as the probabilistic form. In order to capture the realistic sensing characteristics of sensor nodes, in this paper, we introduce the probabilistic sensor detection model given in [15]. The coverage $C(s_i)$ can be calculated by:

$$C(s_i) = \begin{cases} 0 & \text{if } r + r_e \le |s_i p| \\ e^{-\lambda a^{\beta}}, & \text{if } r - r_e < |s_i p| < r + r_e \\ 1 & \text{if } r - r_e \ge |s_i p| \end{cases} \qquad (3.2)$$

where r_e ($r_e < r$) is a measure of the uncertainty in sensor detection, $a = |\, s_i\, p \,| - (r - r_e)$, and λ and β are parameters that measure detection probability when a target is at a distance between $r - r_e$ and $r + r_e$ from the sensor s_i. The probabilistic sensor detection model with different values of the parameters λ and β that yield different translations reflected by different detection probabilities, which can then be viewed as the characteristics of various types of physical sensors. This model reflects the behavior of range-sensing devices wherein the probability of detection decreases along with the distance between the target and the sensor, such as those found in infrared and ultrasound sensors [15], and does not hold true for sensors that only measure local point values such as light, humidity, temperature, etc.

By this model, the yes/no binary detection model can be viewed as a special case wherein the conservative sensing range R_s is $(r - r_e)$. Therefore, the change in detection probabilities with distance can be represented by several concentric circles whose radii are the *probabilistic sensing range*, R_s'. Thus, each circle represents the probability of receiving sensing signals correctly at a distance equal to the radius of the circle. So we can assume that any point within the node s_i's sensing region is lower-bounded by the detection probability $P_d(s_i)$, where $0 < P_d(s_i) < 1$. The less detection probability $P_d(s_i)$ we set, the larger *probabilistic sensing range* R_s' will be generated. From the probabilistic sensor detection model of (3.2), the relationship between $P_d(s_i)$ and R_s' can be estimated by :

$$R_s' = R_s + a = (r - r_e) + \left(-\frac{\ln(P_d(s_i))}{\lambda} \right)^{\frac{1}{\beta}}, \text{ where } R_s' < r + r_e \qquad (3.3)$$

Without a loss of generality, we assume that all of the sensors have the same detection probability $P_d(s_i)$ with the same *probabilistic sensing range* R_s'. For the probabilistic sensing model, we can sacrifice some detection probability to prolong the network lifetime by increasing R_s' such that more sensors can be set in sleeping mode. Thus, the *probabilistic 1-coverage problem* can be reformulated as follows. Given a confidence probability P_c, we want to minimize the number of active nodes under the constraint that the probability in which any point anytime in the monitoring region ***R*** is sensed by at least one node no lower than the threshold P_c.

We now explain how to use our proposed *k*-coverage preserving protocol (CPP) to solve the *probabilistic coverage problem*. We first introduce a parameter k' that represents the *probabilistic coverage degree* when the probabilistic sensing range is set to R_s' under a confidence probability P_c. The *probabilistic coverage degree* k' means that any point in ***R*** is sensed by at least k' sensors, with each having a detection probability $P_d(s_i)$. Our purpose is to find the lower-bound of the cumulative detection probability at any point in ***R***, and it should be no lower than the threshold P_c. Note that the parameter k' is adjustable, so the lower-bound of detection probability $P_d(s_i)$ can be given by:

$$P_c \le 1 - (1 - P_d(s_i))^{k'} \qquad (3.4)$$

When P_c, specified by an application is known, the lower-bound of detection probability $P_d(s_i)$ can be derived from (3.4) if k' is determined. The corresponding sensing range R_s' can be derived from (3.3) if we have $P_d(s_i)$. With the input of k' and R_s', our *k*-coverage preserving protocol can be used to find the set of active nodes. We can then select several values of k' and execute our *k*-coverage preserving protocol in each value of k' to find the best solution. The maximum value k' is restricted by the maximum *probabilistic sensing range* R_s' in (3.3). The value of sensing range increment (or the detection probability decrement) is a trade-off between computational complexity and selection granularity.

Clearly, when the parameter P_c is given, we can execute our *k*-coverage preserving protocol to find out the best solution for solving the *probabilistic 1-coverage problem*. For example, given parameters $(r, r_e, \lambda, \beta) = (5, 3, 0.5, 0.5)$ and P_c = 87.5%, if k' is set to 3, we can compute the detection probability $P_d(s_i)$ from (3.4) as 0.5. After, we then input $P_d(s_i) = 0.5$ to (3.3), where we obtain $R'_s = (5 - 3) + 1.92 = 3.92$. Finally, we run our *k*-coverage preserving protocol with the input $(k', R'_s) = (3, 3.92)$ and the result is a set of active nodes which can guarantee that every point inside ***R*** is covered by at least one sensor with the confidence probability P_c = 87.5%. Note that with different values of k' will generate different results of active nodes.

We can then extend the *probabilistic 1-coverage problem* to the *probabilistic k-coverage problem*. That is, given the required coverage degree k and the confidence probability P_c specified by the applications, we want to minimize the number of active nodes under the constraint that the active nodes must guarantee that the probability of any point anytime in $\boldsymbol{R}$ sensed by at least k nodes is no lower than the threshold P_c. In order to solve this problem, the (3.4) is extended to (3.5):

$$P_c \le 1-\sum_{i=0}^{k-1}\binom{k'}{i}(P_d(s_i))^i(1-P_d(s_i))^{k'-i} \quad (3.5)$$

where k' must be greater than or equal to k. When P_c and k are given, the lower-bound of detection probability $P_d(s_i)$ can be derived from (3.5) if k' is determined. Take note that the (3.4) is the special case in (3.5) when $k = 1$. If we obtain the detection probability, the corresponding sensing range R_s' can be derived from (3.3). We can then execute the k-coverage preserving protocol with inputs k' and R_s' to find out the set of active nodes. For example, given parameters $(r, r_e, \lambda, \beta) = (5, 3, 0.5, 0.5)$ and $(k, P_c) = (2, 87.5\%)$, if k' is set to 3, we have $P_d(s_i) = 0.779$ from (3.5). For $P_d(s_i) = 0.779$, we have $R'_s = (5 - 3) + 0.25 = 2.25$ from (3.3). Finally, we run our k-coverage preserving protocol with the inputs $(k', R'_s) = (3, 2.25)$, and the result is a set of active nodes which can guarantee that every point inside $\boldsymbol{R}$ is covered by at least two nodes with the confidence probability $P_c = 87.5\%$. Given the parameters k and P_c, our protocol can find different numbers of active nodes with different k'. Since the maximum value of k' is small, we can obtain the minimum number of active nodes by trying all possible values for k'.

IV. SIMULATION RESULTS

In order to validate and evaluate the proposed protocol, we use MATLAB combined with the Java language for our simulations. Since the issue we are investigating is the sensing coverage, some other issues such as the MAC layer protocol and routing overhead are ignored by our simulator. Sensor nodes are randomly deployed with uniform distribution in a 120 x 120 m^2 square region and remain stationary once deployed. Each node has the sensing range of 10 m and communication range of 25 m. The monitoring region we defined is the central 100 x 100 m^2 square region to eliminate the edge effect. For the convenience of measurement, we assume each node's lifetime to be 50 minutes if it is active all the time.

In Fig. 4.1, we compare our protocol with the Sponsor algorithm [9] and the CCP [10] in the number of active nodes under various node densities with $k = 1$ or 2. All experiments are repeated 20 times. The lower bound of 1-coverage is built upon a GAF-like algorithm [11], wherein each sensor is deployed in a hexagon-based cell. In our simulation, 45 hexagon cells are required to cover the entire region. We can observe that the number of active nodes is not affected by the node density. The number of active nodes with the coverage degree $k = 2$ is nearly twice the number of active nodes with $k = 1$. The number of active nodes in our proposed protocol is less than 27% that of the CCP when the coverage degree $k = 1$ and the number of active nodes in our proposed protocol is less than 31% that of the CCP when the coverage degree $k = 2$. This is because our proposed protocol can choose every active node precisely compared to the eligibility rule in CCP, which is a decentralized algorithm that turns off every redundant node. The result in the Sponsor algorithm shows the worst performance because it must increases the active nodes along with the number of deployed nodes as the sensor network increases. The performance of our k-coverage preserving protocol is very close to the lower bound in 1-coverage and can be used in the probabilistic k-coverage protocol.

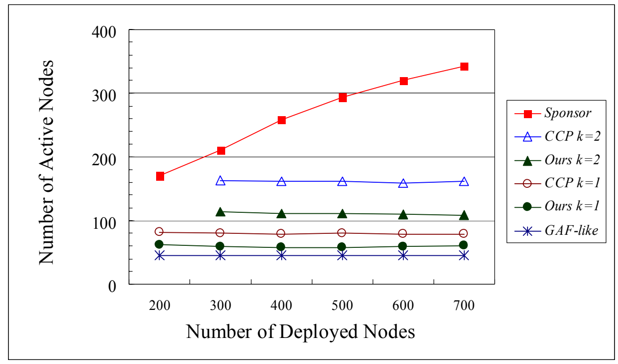


Figure 4.1: The number of active nodes with different node densities

Here, we implement the probabilistic k-coverage protocol and evaluate the performance in terms of the number of active nodes. All experiments are repeated 100 times and the results include the average number of active nodes and the variances with various confidence probabilities. We deploy 400 sensor nodes in the 20 x 20 m^2 monitoring region and assume the parameters $(r, r_e, \lambda, \beta) = (5, 3, 0.5, 0.5)$. Thus, the conservative sensing range R_s is 2 m and the *probabilistic sensing range* R_s' is smaller than 8 m, based on (3.2). In Fig. 4.2, we let the required coverage degree $k = 1$ and the confidence probabilities P_c to be 95%, 90%, 85%, and 80%, respectively. The parameter k' is given from 1 to 5 since the region $\boldsymbol{R}$ has at most 5-covered even $R'_s = 8$ m. We can obtain the value of R_s' by (3.3) under a selected k' and a specified P_c. We then execute our k-coverage preserving protocol with different input values of k' and its corresponding R'_s. The output result is guaranteed that every point inside region $\boldsymbol{R}$ is covered by at least one node with a specified confidence probability P_c. We then choose a specific value k', which produces the minimal number of active nodes, as our final result. For instance, in Fig. 4.2, the best result is $k' = 1$ when $P_c = 95\%$. On the other hand, the best result is $k' = 5$ when $P_c = 85\%$.

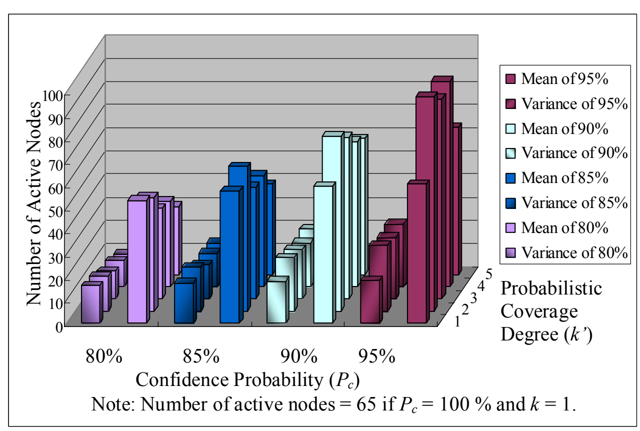
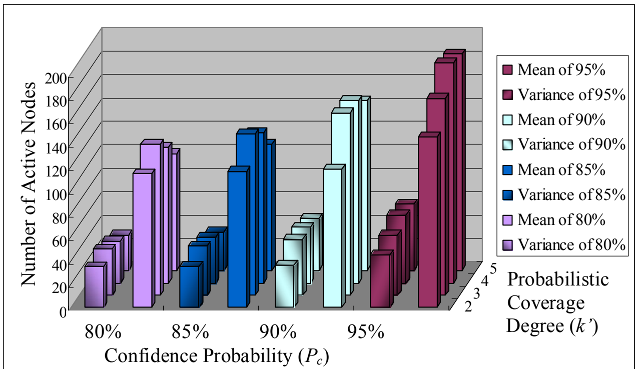


Figure 4.2: The number of active nodes with different P_c and k' when $(r, r_e, \lambda, \beta) = (5, 3, 0.5, 0.5)$ and $k = 1$

The required coverage degree k in Fig. 4.3 is set to 2 and parameter k' is given from 2 to 5 ($k' \geq k$). Under a specific P_c and k', we can obtain different values of R_s' from (3.5) and (3.3). We run our k-coverage preserving protocol with different values of k' and its corresponding R_s' to find out which one has the minimum number of active nodes. For instance, when P_c = 90%, we acquire the minimal number of active nodes equal to 118 as k' = 2. For another instance, when P_c = 80%, we have the minimal number of active nodes equal to 99 as k' = 5. The results show that we can find the best solution by executing the k-coverage preserving protocol a finite number of times under the specific confidence probability P_c and coverage degree k.



Note: Number of active nodes = 148 if P_c = 100 % and k = 2.

Figure 4.3: The number of active nodes with different P_c and k' when (r, r_e, λ, β) = (5, 3, 0.5, 0.5) and k = 2

In Fig. 4.4, we show the simulation results for different parameters λ and β, which can be viewed as the characteristics of different types of physical sensors. The required coverage degree k is set to 1 or 2, and parameter k' varies, from 1 to 5. We can see that the number of active nodes in Fig 4.4 is less than that in Figs. 4.2 and 4.3, under the same confidence probability P_c and k'. This is because the sensing range R_s' along with (λ, β) = (0.3, 0.5) is larger than the sensing range of R_s' with (λ, β) = (0.5, 0.5) under the same detection probability $P_d(s_i)$. Thus, different detection probability models have different performance representations.

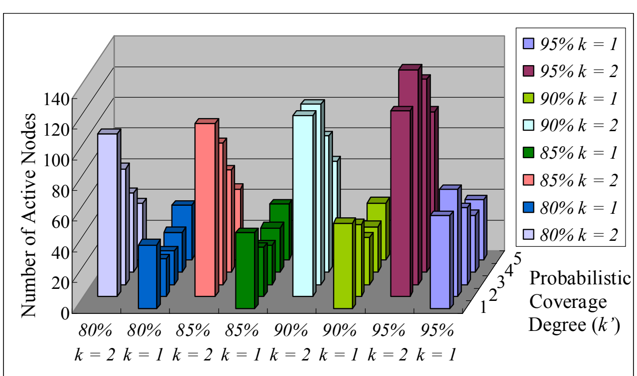


Figure 4.4: The number of active nodes with different P_c and k' when (r, r_e, λ, β) = (5, 3, 0.3, 0.5)

V. CONCLUSION

Coverage problem is a major challenge in wireless sensor networks. The main contribution of this paper is to introduce the probabilistic coverage model to achieve energy efficiency and to guarantee the sufficient degree of coverage in the sensor networks. We deal with the coverage problems in the most general form by including yes/no coverage decision problems, k-coverage problems, and probabilistic k-coverage problems. Under the coverage constraint, the purpose of our proposed protocol is to select the minimal active set of sensor nodes to approach the best energy conservation method. The simulation shows that our k-coverage preserving protocol is close to the performance of lower bound. From the results in the simulation of probabilistic coverage, we can certainly find the best solution among the number of k's which have the minimum number of active nodes, and can result in saving total energy consumption.

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